

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 25-01-2007		2. REPORT TYPE Final Report		3. DATES COVERED (From – To) 01-Apr-02 - 29-Jan-07	
4. TITLE AND SUBTITLE Development of a database on the changes in the optical properties of materials used on the external surfaces of spacecraft under the action of the space environment factors			5a. CONTRACT NUMBER ISTC Registration No: 2342P		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Dr. Sergey A Khatipov			5d. PROJECT NUMBER		
			5d. TASK NUMBER		
			5e. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Moscow State Engineering Physics Institute Kaluga Region Obrninsk 249033 Russia			8. PERFORMING ORGANIZATION REPORT NUMBER N/A		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD PSC 821 BOX 14 FPO AE 09421-0014			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) ISTC 01-7010		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <p>The purpose of the project was a development of the Database (DB) in the electron format DBMS Access2000, including results of investigation of optical properties of external materials for space vehicles (SV) under conditions of space environment factors (SEF). The data base was compiled on the basis of literature data, as published in the open sources within the recent 30 years, concerning degradation of optical properties of materials under in-flight and laboratory conditions, and also on the basis of new experimental data as obtained within the framework of the present project.</p> <p>Within the framework of the present project, laboratory testing for materials applied to external surfaces of SV were carried out under the action of UV-radiation, electrons having an energy of 40, 100 and 200 keV, and also protons having an energy of 40, 150, 300 and 500 keV. Testing was performed for the case of separate action of each of the factors mentioned on the material. The maximum level of an exposure dose, which was reached while performing laboratory testing, amounted up to 1 equivalent solar year under conditions of GEO for the UV-radiation. From 1 to 2 years under conditions of the orbit crossing radiation belts of the Earth for electrons and protons.</p> <p>The objects to be investigated were thermal control coatings (8 trade marks), fabrics (6 trade marks), polymeric films (3 trade marks), solar array elements (6 trade marks).</p> <p>The main material characteristics for materials were: integral and spectral coefficients of electromagnetic radiation absorption, reflection and transmission, coefficient of thermal radiation, angular dependency for reflected and transmitted electromagnetic radiation within the plane of beam incidence. The characteristics mentioned were measured before and after a radiation action, and also in the course of radiation action for different values of the dose absorbed.</p> <p>The total volume of the Data Base amounted up to approximately 2600 records, as represented in tabular and graphical form.</p>					
15. SUBJECT TERMS Spacecraft materials, optical properties, space environment, EOARD					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 27	19a. NAME OF RESPONSIBLE PERSON BARRETT A. FLAKE
a. REPORT UNCLAS	b. ABSTRACT UNCLAS	c. THIS PAGE UNCLAS			19b. TELEPHONE NUMBER (Include area code) +44 (0)20 7514 4285

ISTC 2342p

**Final
Project Technical Report
of ISTC 2342p**

**Development of a database on the changes in the optical properties of
materials used on the external surfaces of spacecraft under the action
of the space environment factors**

(From 1 April 2002 to 30 September 2006 for 54 months)

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(Project Manager)
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(State University)**

September 2006

This work was supported financially by European Office of Aerospace Research and Development (EOARD, London) and performed under the contract to the International Science and Technology Center (ISTC, Moscow).

ISTC 2342p

Development of a database on the changes in the optical properties of materials used on the external surfaces of spacecraft under the action of the space environment factors
(From 1 April 2002 to 31 December 2005 for 45 months)

Sergey Amerzhanovich Khatipov (Project Manager)
Moscow State Engineering Physics Institute (State University)*

The purpose of the project was a development of the Database (DB) in the electron format DBMS Access2000, including results of investigation of optical properties of external materials for space vehicles (SV) under conditions of space environment factors (SEF).

The data base was compiled on the basis of literature data, as published in the open sources within the recent 30 years, concerning degradation of optical properties of materials under in-flight and laboratory conditions, and also on the basis of new experimental data as obtained within the framework of the present project.

Within the framework of the present project, laboratory testing for materials applied to external surfaces of SV were carried out under the action of UV-radiation, electrons having an energy of 40, 100 and 200 keV, and also protons having an energy of 40, 150, 300 and 500 keV. Testing was performed for the case of separate action of each of the factors mentioned on the material. The maximum level of an exposure dose, which was reached while performing laboratory testing, amounted up to 1 equivalent solar year under conditions of GEO for the UV-radiation. From 1 to 2 years under conditions of the orbit crossing radiation belts of the Earth for electrons and protons.

The objects to be investigated were thermal control coatings (8 trade marks), fabrics (6 trade marks), polymeric films (3 trade marks), solar array elements (6 trade marks).

The main material characteristics for materials were: integral and spectral coefficients of electromagnetic radiation absorption, reflection and transmission, coefficient of thermal radiation, angular dependency for reflected and transmitted electromagnetic radiation within the plane of beam incidence. The characteristics mentioned were measured before and after a radiation action, and also in the course of radiation action for different values of the dose absorbed.

The total volume of the Data Base amounted up to approximately 2600 records, as represented in tabular and graphical form.

Key words: external materials of space vehicles; space environment factors; UV-radiation; electrons; protons; optical characteristics; the Data Base is in the format of DBMS Access2000

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Contents

1. Introduction	5
2. Description of the work plan	6
2.1. Scope of activities	6
2.2. Technical approach	8
2.3. List of materials to be acquired for testing	9
2.4. Summary of technical progress	15
3. Methods of test	18
3.1. Testing of material samples under the action of protons having energy of 150, 300 and 500 keV	18
3.2. Irradiation of samples with electrons with the energies 100 keV and 200 keV	21
3.3. Testing of material samples under the action of electrons, protons and electromagnetic radiation on the UV-1/2 installation	26
3.4. Measurement of reflection and scattering indicatrices (BRDF, BSDF) for materials and coatings within a spectral range of (0.3-2.5 micron)	30
3.5. Measurement of the coefficient of solar radiation absorption α_s	35
3.6. Measurements of integral emission ability ϵ for materials and coatings	36
3.7. Measurements of the spectral coefficient for the total diffuse and mirror reflection in the region of wave lengths of 0.22-2.6 micron	37
4. Current status of the progress of the technical work	39
5. Cooperation with foreign collaborators	39
6. Information concerning usage of the project results	39
7. Appendix 1. References	40
8. Appendix 2. Examples of Data base	44
9. Appendix 3. The Data base in the electron format DBMS Access2000 (2600 records)	

1. Introduction

1. Purpose of the Project. To develop a Database on the changes in the optical properties of materials used on the external surfaces of spacecraft, based on the results of both in-flight and laboratory simulation tests.

2. Current State of Affairs in the Field of Research. Currently, there exist a large number of studies in the stability of the optical properties of materials used on the external surfaces (blankets, thermal control coatings, solar arrays etc.) of spacecraft. These studies have been based on experimental results obtained both in laboratory and actual in-flight conditions. All of them, particularly [1 — 9], confirm the fact that the factors of the space environment (FSE) exercise a strong influence both on the spectral and the integral optical parameters of the materials. Optical degradation of external surfaces may result in a change of the thermal regime of a spacecraft, in a malfunction of its orientation and communication systems and ultimately in the stoppage of its active functioning. In this connection, the problem of predicting changes in the optical properties of materials has always attracted the closest attention in world scientific literature. Predicting the aforementioned changes has become of particular importance recently, in connection with the trend to increase the lives of spacecraft up to 10 — 20 years, as well as with the development of spacecraft electronic surveillance and identification systems. The process of creating a method for the long-term prediction of changes in the optical properties involves several stages. The principal ones are the following: developing physical and mathematical models to describe the degradation of the optical properties [e. g. 3, 7, 10] and testing the validity of such models with regard to specific types of materials. In order to solve the problems posed by each of the above stages, it is necessary to create databases that will include the results of in-flight and laboratory tests. It is only on the basis of extensive experimental material presented in such databases that reliable empirical models describing the effects of the aging of space materials can be built and their validity can be tested in regard to specific materials and operation conditions. Currently, the use of such databases both in Russia and worldwide is quite limited, whereas literary sources contain considerable amounts of experimental data that have not been given systematic form in electronic database format.

3. Effect of the Project on Scientific Progress in the Field. Achieving the purpose of the project contributed to the development of methods for the long-term prediction of the effects of space aging and, ultimately, to increasing the active life of spacecraft. A number of new experimental results were obtained in the study of the spectral parameters for the space materials. Close attention was paid to the data available in literature on new promising materials for use on the external surfaces of spacecraft. It was conducted tests of certain new types of thermal control coatings (TCCs) and elements of solar arrays. The project includes: (1) analysis, selection and systematization of data, available in published sources and obtained in the last 30 years, on changes in the optical parameters of blankets, thermal control coatings, solar arrays etc. in actual conditions of the space environment on LEOs and GEOs; (2) developing the structure and user interface of the Database with the help of the Access '2000 software or later version; (3) entering the data into the Database; (4) testing of optical parameters for the most widespread and promising external surface materials of spacecraft under the action of electromagnetic solar radiation and accelerated electrons and protons.

4. Expertise of the Project Participants in the Given Field. The project gives the “weapons” scientists involved in it — experts in the field of missile materials and technologies — a chance to apply for peaceful purposes some directions and results of their earlier research in developing and testing materials intended for special military equipment. The participants of the project have been taking an active part in studying the effects of the space environment factors on the properties of such materials for many years. These directions of research have been given a high priority at the institutions these scientists represent: MIFI, NIIYaF MGU, IKI. Results obtained by the authors have been presented in numerous papers, monographs and scientific reports. Some of the publications by the project participants are enumerated below (Appendix 1).

2. Description of the work plan

2.1. Scope of activities

The project was carried out by research workers from three institutions: MIFI, IKI and NIIYaF MGU. It included three stages.

The first stage (first year) of the project was carried out using the facilities and personnel of MIFI. Its purpose was to sum up the data available in published sources concerning the study of the optical and thermo physical properties of space materials and, based on them, to create a Database in electronic format. This stage presupposed developing the structure of the Database using standard database software (MS Access 2000 or later), as well as filling in the latter with the data selected from published sources at this stage of the effort.

The second stage (the second year) of the project was carried out using the facilities and personnel of MIFI, NIIYaF MGU and IKI. Its purpose was (1) conducting tests of materials under the action of electromagnetic solar radiation with exposures equivalent to up to 1 year of 1-sun (2) conducting tests of materials under the action of accelerated electrons (50-250 keV up to a fluence of 10^{16} cm^{-2}) and protons (50-500 keV up to a fluence $2 \times 10^{16} \text{ cm}^{-2}$), (3) processing and entering the test results into the Database, (4) continuing to fill in the Database with information from published sources.

The third stage (year) of the project was carried out using the facilities and personnel of three institutions: MIFI, NIIYaF MGU and IKI and has as its purpose the continuation and completion of the studies under all the four headings stated above for the second stage.

Connecting with registering license on transfer of final report to the partner, this project was prolonged for the unpaid term since 01.04.2005 to 31.12.2005. For the period license was obtained. The report containing Database (DBMS Access 2000) was sent to the partner (EOARD, London).

For improving structure of Database this project was prolonged for the paid term since 01.04.2006 to 30.09.2006. Within the prolongation period, the following results was obtained:

- 1) the Data base structure will be modified on the basis of DBMS Access2000 with the purpose of providing a possibility for the selection of an data array to ensure the maximum possible combination of the request parameters;
- 2) exporting the results of testing, as represented in the graphical form in the figure format, will be performed into the tabular format of the program Excel2000, and afterwards into the format of DBMS Access2000;
- 3) material samples (thermal control coatings, fabrics, films, solar array elements) will be procured to investigate space aging effects;
- 4) final scientific – technical report including Data base on CD-disc having a license for exporting will be delivered to the partner (EOARD, London);

Thus the project was completed by creating Database including 2600 records, which contain new results on research optical properties of materials irradiated by protons, electrons and electromagnetic solar radiation. Final result of this work is presented by the report including (a) list applied materials, (b) list sources of information for the Database, (c) describing of structure the Database, (d) the Database (DBMS Access 2000).

The general work plan:

Task 1 (Period of implementing: 01.04.02 – 31.03.2005)

Task description and main milestones

Developing a Database on the effect of the space environment factors on the optical properties of materials used on the external surfaces of spacecraft.

The work is carried out using the facilities and personnel of MIFI.

1. Analyzing and selecting results of tests of spacecraft materials in laboratory and in-flight conditions from published sources.
2. Developing the structure and user interface of the Database.
3. Processing the data and entering them into the Database.

Description of deliverables

1. Quarterly, yearly and final scientific reports including: a list of the investigated materials, a list of the processed information sources, a description of the Database structure and samples of the Database. Third quarterly report to include the list of materials for testing and the plan of testing for the 2nd and 3rd years.
2. The Database in Access 2000 (or later version of MS Access) electronic format.

Task 2. (Period of implementing: 01.04.03 – 31.03.2005)

Task description and main milestones

Conducting tests of materials used on the external surfaces of spacecraft (solar arrays, blankets, thermal control coatings etc.) under the action of electromagnetic solar radiation.

The work is carried out using the facilities and personnel of MIFI and IKI.

1. Testing the materials under the action of electromagnetic solar radiation.
2. Processing and entering the results of the tests into the Database.

Description of deliverables

1. Quarterly scientific reports including: a list of the investigated materials, a list of the processed information sources, a description of the experimental technique.
2. Samples of the Database, including results of the conducted tests.
3. Samples of pristine and space aged materials in an inert environment for analysis in the US

Task 3. (Period of implementing: 01.04.03 – 31.03.2005)

Task description and main milestones

Conducting tests of materials used on the external surfaces of spacecraft (solar arrays, blankets, thermal control coatings etc.) under the action of accelerated protons and electrons.

The work is carried out using the facilities and personnel of MIFI and NIIYaF MGU.

1. Testing the materials under the action of accelerated electrons in the energy range 50 — 250 keV.
2. Testing the materials under the action of accelerated protons in the energy range 50 — 500 keV.
3. Processing and entering the results of the tests into the Database.

Description of deliverables

1. Quarterly scientific reports including: a list of the investigated materials, a list of the processed information sources, a description of the experimental technique.
2. Samples of the Database, including results of the conducted tests.
3. Samples of pristine and space aged materials in an inert environment for analysis in the US

Task 4. (Period of implementing: 01.04.03 – 31.03.2005)

Task description and main milestones

Studying the changes of the optical properties of materials used on the external surfaces of spacecraft (solar arrays, blankets, TCCs etc.) after the action of the space environment factors.

1. Studying the spectral properties (coefficients of absorption, reflectance and transmission of solar radiation, optical density).
2. Studying the integral properties (coefficients of absorption, reflectance and transmission of solar radiation, optical density, bi-directional reflectance distribution function, coefficient of heat emission to a hemisphere and changes of sample color and appearance).

Description of deliverables

1. Description of the experimental technique of measuring the optical properties.
2. Spectra of the optical parameters of the materials with changing the intensity of the factor acting upon the sample.
3. Samples of the Database, including results of the conducted tests.

Task 5
Task description and main milestones
<p><u><i>Digitizing the Data base.</i></u></p> <p><u>Purpose:</u> expanding possibilities for selecting data arrays in the digital format.</p> <p>The works are performed on the MIFI base.</p> <ol style="list-style-type: none"> 1. Exporting results of testing, as represented in the graphical form in the figure format, into the tabular format of the program Excel2000. 2. Exporting results of testing, as represented in the tabular format of the program Excel2000, into the format of DBMS Access2000 in the graphical and digital forms.
Description of deliverables
<ol style="list-style-type: none"> 1. Quarterly reports. 2. Final technical report including the Data base in the electronic format of DBMS Access 2000. Export of final technical report including the Data base on CD-disc having a license for exporting to the partner (EOARD, London) via DHL post through ISTC;

Task 6
Task description and main milestones
<p><u><i>Modifying the Data base structure.</i></u></p> <p><u>Purpose:</u> ensuring the maximum possible amount of request parameter combinations for selecting data arrays in the digital and graphical forms.</p> <p>The works are performed on the MIFI base.</p> <ol style="list-style-type: none"> 1. Modifying a system of links for information fields of the Data base in the format of DBMS Access2000.
Description of reporting materials.
<ol style="list-style-type: none"> 1. Quarterly reports. 2. Final technical report including the Data base in the electronic format of DBMS Access 2000. Export of final technical report including the Data base on CD-disc having a license for exporting to the partner (EOARD, London) via DHL post through ISTC.

2.2. Technical Approach

During the first stage, the Database was developed on the basis of published sources, such as monographs, articles in scientific journals, proceedings of conferences and symposiums. The structure and user interface of the Database was developed with the help of standard software: MS Access 2000 (or later). They allowed searching for and selecting data by material type and name, by physical parameter, space environment factor, type of test, etc. The Database contains the data in both graphical and table form. Each record in tables or forms of the Database corresponds to no more than one functional dependence. The reduction of the number of curves on one graph in one record or of the number of data represented in one record in table form was promoting the expansion of search and information processing capabilities.

Tests under the action of electromagnetic solar radiation has been conducted with exposures equivalent to up to 1 year of 1-sun on the geostationary earth orbit (GEO). The dependence of the optical parameters on the irradiation time for each material has been determined for four values of the exposure. After the required value of the irradiation time has been reached, the samples were taken out of the test chamber and placed into an environmental container had filled with inert gas.

Irradiation of materials with accelerated electrons was conducted for electrons with the energies 50, 100, 250 keV, with the fluence reaching $\Phi_e \approx 10^{16} \text{ cm}^{-2}$ and the flux density not exceeding $5 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ (which is approximately equivalent to 10^2 Gy/s). For low-energy electrons (with energies less than 100 keV), the total absorbed dose on the material surface was approximately equal to the annual surface dose on an orbit that crosses the radiation belts of the Earth. For electrons with the energy greater than 100 keV, these doses exceeded the annual level on such orbits by approximately 2 times. The dependence of the optical parameters on the irradiation time for each material has been determined for four values of the fluence of electrons, similarly to what was planned to do in the case of electromagnetic solar radiation. After irradiation, the samples were also placed into an environmental container had filled with inert gas.

Irradiation of materials with accelerated protons was conducted for protons with the energies 50, 150, 300, 500 keV, with the fluence reaching $\Phi_p \approx 2 \times 10^{16} \text{ cm}^{-2}$ and the flux density not exceeding $5 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$. For protons in the energy range 150 to 500 keV, the total dose absorbed on the material surface was approximately equal to the annual level absorbed on orbits crossing the radiation belts. The dependence of the optical parameters on the irradiation time for each material has been determined for four values of the fluence of protons. For the energies 150, 300 and 500 keV, measurement of α_s was taken place directly in the vacuum chamber. In order to study the effect of 'bleach,' the results of measurements in vacuum were compared to those obtained after storage of the samples in air and in an inert medium.

The following optical parameters were measured:

- for opaque reflective materials (thermal control coatings, etc.):
 α_s , ρ_λ , ρ_s , ε , BRDF (measurements to be carried out for two angles of incidence of the ray: 0 and 70°), change of appearance and color (by eye)
- for transparent scattering materials (fabrics, etc.)
 ρ_λ , α_s , T_λ , T_s , ε , change of appearance and color (by eye)
- for transparent materials (non-metallized polymer films and glasses, etc.)
 ρ_λ , α_s , T_λ , T_s , ε , D , D/x , change of appearance and color (by eye)
- for mirror surfaces (metallized polymer films, polished metal surfaces, etc.)
 ρ_λ , α_s , ρ_λ , ρ_s , ε , BRDF (measurements to be carried out for two angles of incidence of the ray: 0 and 70°), change of appearance and color (by eye)

2.3. List of materials to be acquired for testing

The listed materials are generally available and widely used in spacecraft. Test results for these materials in laboratory and in-flight conditions have been published in Russian and foreign scientific literature. One of goals of the project was the systematization of the known data and obtaining new ones for the listed materials. The materials were purchased from the following companies: NPO Kompozit, NPO Lavochkin, NPO Kvant. The technical requirements for the production technology, the particular brands of materials, as well as the possibility of using them within the framework of the Project, have been coordinated with the above-mentioned organizations.

2.4. Summary of Technical Progress

According to the working plan of the project it was performed items 1,2 and 3 of task 1, items 1 and 2 of task 2 items 1,2 and 3 of task 3, items 1 and 2 of task 4 in addition to items and tasks of the term prolongation of project since 01.04.2006 to 30.09.2006: items 1,2 of task 5 (digitizing of the Database) and item 1 of task 6 (improving of structure the Database). All items and tasks were completed.

Under Item 1 of Task 1, the work of analyzing and selecting test results for materials from information sources has been carried out. The list of these information sources is given in the Appendix. The following results, contained in the published sources listed below, have been selected for entering into the Database:

- pristine optical and thermophysical parameters of TCCs, fabrics, metallized and non-metallized glasses and polymer films, solar arrays, structural and optical materials, lacquer and paint coatings, MLIs, pigments used in TCCs [1, 4, 16 – 21, 44, 45, 47, 49 – 51, 57, 58, 60, 61];
- results of laboratory tests for the listed materials under the action of UV radiation, accelerated electrons and protons [1, 4, 16 – 19, 21, 25, 27, 28, 32 – 43, 45, 48, 52 – 56, 59 – 63];
- results of laboratory tests for TCCs in conditions modeling those in orbits that cross and do not cross the radiation belts of the Earth [29, 30, 33 – 35, 38];
- results of in-flight tests for materials in LEOs (Salyut-6, Salyut-7, Almaz, Mir) [26, 29, 30, 31];
- results of in-flight tests for TCCs in HEOs and GEOs on board the space vehicles Molniya, Raduga, Gorizont and others with exposure times in open space of up to 10 years and estimates of the change of α_S for up to 10 years in GEOs, based on the data of laboratory tests [24];
- results of laboratory tests of light resistance for materials used on the external surfaces of spacecraft with exposure times in open space of up to 15 years [56];
- kinetic models of degradation for TCCs under the action of UV, atomic oxygen, electrons and protons [18, 22, 23, 29, 32 – 35];
- study results of the kinetics of ‘bleach’ for TCCs after irradiation with UV, electrons and protons [16 – 19, 38];
- others.

Under Item 2 of Task 1, a structure of the Database has been developed that allows to systemize and to represent as fully as possible the above-mentioned test results in electronic format. The developed version of the DB structure includes fifteen tables and eight forms.

The list of these tables is given in Figure 1 of Appendix 2.

The table of materials (tbl_MaterialList) contains the following information fields (Figure 2 of Appendix 2):

- auto-number (unique identifier)
- name of the material;
- type of the material;
- chemical composition of the material;
- peculiarities of the fabrication method of the material;
- application of the material;
- reference to the state standard for the manufacture of the material.

The types of materials are presented in `tbl_TypeMaterials` (Figure 3). The materials are divided into seven types. The materials that do not come under any of the itemized types are presented in the 'others' category:

- fabrics,
- MLIs,
- thermal control coverings,
- solar arrays,
- structural materials,
- optical materials,
- others.

TCCs are subdivided into the following classes (Figure 4, Appendix 2):

- enamels,
- silicate coverings,
- galvanochemical coverings,
- metallized films,
- non-metallized films,
- metallized glasses,
- non-metallized glasses,
- others.

Structural materials (`tbl_TypeStructuralMaterial`) used on the external surfaces of spacecraft are subdivided into five types (Figure 5, Appendix 2):

- glass plastics,
- thermoplastics,
- carbon plastics,
- metals,
- alloys,
- other.

The table of the type of tests (`tbl_TypeTests`) includes (Figure 6, Appendix 2):

- in-flight tests,
- laboratory tests,
- prediction results.

The factors of the space environment (`tbl_SpaceFactors`) are divided into following classes (Figure 7, Appendix 2):

- electrons,
- protons,

- ultraviolet solar radiation,
- infrared and visible solar radiation,
- vacuum ultraviolet,
- soft X-ray radiation,
- combined action of electrons and protons,
- combined action of electrons, protons and ultraviolet solar radiation,
- atomic oxygen,
- combined action of atomic oxygen and ultraviolet solar radiation,
- thermocycling,
- contamination,
- complex action of the space environment factors,
- others.

The list of optical and thermophysical parameters is given in tbl_Parameters (Figure 8, Appendix 2):

- solar absorption,
- spectral absorption coefficient,
- solar reflectance,
- spectral reflectance,
- solar transmittance,
- spectral transmittance,
- coefficient of heat emission,
- spectral coefficient of heat emission,
- optical density,
- relative optical density reduced to the unit of the sample thickness,
- change of material color and appearance,
- Bi-directional Reflectance Distribution Function (BRDF),
- coefficient of thermal conductivity,
- coefficient of thermal diffusivity,
- specific heat capacity,
- melt temperature,
- density,
- others.

Orbits (tbl_TypeOrbits), taking into account the operating conditions of spacecrafts in them, are divided into types as follows (Figure 9, Appendix 2):

- Low Earth Orbit (LEO, 200 - 600 km, $i = 0 - 90^\circ$)
- Low Earth Orbit (LEO, 600 - 1000 km, $i < 65^\circ$)
- Middle Earth Orbit (MEO, 1000 - 36000 km, $i < 90^\circ$)
- Polar Orbit (POL, 600 - 1000 km, $i > 65^\circ$)
- Geostationary Earth Orbit (GEO, 36000 km, $i = 0^\circ$)
- High-elliptical Earth Orbit (HEO, 500 - 40000 km, $i = 65^\circ$)

The table tbl_References contains a list of the information sources. The imprint of the publications, such as the author's name, title, and the publisher, is presented in the table. (Figure 10, Appendix 2).

The results of material tests have been distributed into six tables in accordance with the division of materials into six types. Test results for each of the six material types are entered into a

separate table linked to the other tables. The structure of the data tables is presented in Figure 11 with TCCs as an example. For the other types of materials, the structure of tables is similar.

For the presentation of the test results, 6 forms have been developed; each of them linked to one of the 6 data tables that, in turn, correspond to the 6 types of materials (fabrics, MLIs, TCCs, solar arrays, optical and structural materials). Figures 12-15 show examples of records from the TCC, fabric and structural data tables in a data forms. The data form has a similar appearance for the other types of materials.

As for Items 3 (Task 1), 2 (Task 2) and 3 (Task 3), processing and input of literature source data into the Data Base were performed. The Data Base volume, as based on literature sources, amounts up to approximately 1000 entries.

As for Items 1 (Task 2), 1 and 2 (Task 3), 1 and 2 (Task 4). testing was performed for materials under the action of electrons, protons, and electromagnetic irradiation simulating solar irradiation. The experimental results obtained are inputted into the Data Base in the form of diagrams and tables. The Data Base volume amounted up to approximately 2600 entries in view of data obtained within the frame of the project.

In order to perform **all items of tasks 5 and 6**, the standard programs for digitizing graphical data have been used. Having digitized, the data were exported first into the format of program Excel 2000, and then into the format of program Access 2000. In order to modify the Data base structure, there has been used a standard software as involved in DBMS Access 2000. This software was used to create a necessary network of information field links. This allowed all the data to be relational.

The short description of experimental devices, which were used to perform experiments, is provided below.

3. Methods of Test

3.1. Testing of material samples under the action of protons having energy of 150, 300 and 500 keV

The device for having materials tested under the proton action is created on the basis of cascade electrostatic accelerator KG-500. The accelerator makes it possible to obtain continuous beam of protons having fixed energies within the range of 100 to 500 keV, in particular 150, 300 and 500 keV, as envisioned by the given project. The stability of proton energy is 0,1 %. The proton beam current may reach 200 microampere at the target. The beam current stabilization is 1 %.

Proton irradiation of the material samples was carried out in the following order.

Before irradiation:

- a standard sample and up to 5 samples for testing are installed on a rotary disk;
- the rotary disk is fastened to the chamber flange;
- the values of the graduated limb marked on the disk are recorded after fixing each sample to be tested in its place of irradiation (the slot on the disk next to the sample is matched with the entrance slot of the Faraday cylinder for monitoring protons);
- the chamber is pumped out;
- after the pressure in the chamber reaches $\sim 5 \times 10^{-6}$ mm mercury column, the standard sample is placed on the same plane as the entrance aperture of the photometric head and the measuring device (M-95 micro ammeter) is set at a value that corresponds to its α_s ;
- with successively fixing each of the samples for testing, the pristine-state values of α_s are measured with the photometer and the position of the samples is recorded based on limb values.

Injecting the proton beam:

- the proton beam reaches the adjusting Faraday cylinder and the required value of the beam current is established;
- after opening the flag-shutter, the proton beam reaches the quartz plate fastened to the rotary disk;
- based on the luminescence brightness of the quartz plate and via consecutively measuring the values of the beam current on the lamels located near the quartz plate, the vertical scanning is adjusted with high-frequency voltage with the purpose of achieving homogeneous distribution of the flux density of the proton beam
- the saw tooth voltage generator is turned on for horizontally scanning the proton beam and final adjustment of the beam is carried out.

Irradiating the samples and measuring their α_s :

- the sample to be tested is set up in its place of irradiation using the limb values;
- a preset of pulses is set on the scale, proportional to the required value of the protons fluence;
- the automatic irradiation system is turned on;
- in each period of the horizontal scanning of the beam, the entire surface of the sample is irradiated and the fluence of protons during this period is recorded;
- on reaching the pulse size determined by the preset, the proton beam is automatically shut off by the flag-shutter;
- the α_s of the irradiated sample is measured in the vacuum chamber.

In accordance with the procedure described, there have been carried out measurements of the dependence of $\Delta\alpha_s$ on the time of irradiation with protons with the energies 150, 300 and 500 keV for all the 23 material brands under investigation. Measurements were carried until the maximum fluence value, equal to $2 \times 10^{16} \text{ cm}^{-2}$, was reached, after which the samples were taken out into the air and the spectral parameters and BRDFs were measured on them. Some of the materials were irradiated up to intermediate values of the absorbed fluence and the spectral parameters and BRDFs were measured on these in air as well.

3.2. Irradiation of Samples with Electrons with the Energies 100 keV and 200 keV.

The requirements for irradiating the samples included the following:

1. 23 types of samples to be uniformly irradiated with electrons;
2. Electron energy to be 100 keV and 200 keV;
3. Irradiation to be carried out in vacuum under a pressure of no worse than 10^{-2} Pa ;
4. Average electron flux density not to exceed $j_{\text{aver}} < (1 \div 5) \cdot 10^{12} \text{ part/cm}^2 \text{ s}$;
5. Irradiation dose to be $(1 \div 2) \cdot 10^{16} \text{ part/cm}^2$;
6. Temperature of the samples during irradiation not to exceed $+30^\circ\text{C}$;
7. 2 samples of the same type to be irradiated at a given energy value; after irradiation, one sample to be stored in a container filled with argon and one to be stored in air.

The most difficult task faced by us was obtaining uniform homogeneous irradiation field for the simultaneous treatment of several samples. The experiment being conducted on the electron injector of a linear accelerator, where the diameter of the electron beam at the output does not exceed 6 mm, there were two ways in which the task set before us could be solved: either by creating a system of scanning the beam or by artificially increasing its transverse size.

The first way is quite complicated and, the installation working with the frequency 1 Hz, this solution would have resulted in a significant increase of the irradiation time of the samples. With this in mind, the decision was made to follow the second option.

An acceptable irradiation field with $j_{\text{aver}} \sim 5 \times 10^{12} \pm 30\% \text{ part/cm}^2 \text{ s}$ was obtained without a magnetic screen with adjusting the position of the beam in the vertical and horizontal planes. Shown in Fig. 7 is the distribution of the current on the target surface at $j_{\text{aver}} = 5 \times 10^{12} \text{ part/cm}^2 \text{ s}$. In this case, $I_c = (1 \div 1.5) \text{ A}$; the current on the total surface of the target is $I_c \approx (0.6 \div 0.8) \text{ A}$. During the time of irradiation, the distribution of the field changes: intensity increases in the lower part of the target. Numerous experiments have shown that, in order to preserve the distribution of currents shown in Fig. 7, it is sufficient to perform adjustment of the beam at the 20th and 40th minutes of irradiation. The irradiation field obtained has allowed processing four material samples simultaneously. The irradiation time depended on the value of the current and ranged from 40 minutes to 60 minutes.

3.3. Testing of material samples under the action of electrons, protons and electromagnetic radiation on the UV-1/2 installation

The test bench consists of three main parts:

- the vacuum module, with the pumping system and the vacuum control system;
- the block of simulators of the space environment factors;
- the automated system of measurement and control.

In the course of irradiation, the samples were four times removed into the open air, where an integral solar radiation reflection coefficient was measured within several minutes using FM-59 photometer, through which a change in the absorption density $\Delta\alpha_s$ was calculated. Upon finishing irradiation, one of the material samples was immediately put into an argon container, and another one was removed into the open air for measuring spectral characteristics and scattering indicatrices. Using the installation described, dependencies of $\Delta\alpha_s$ on the time of electron, proton and electromagnetic radiation irradiation were measured for all the 23 materials investigated.

3.4. Measurement of reflection and scattering indicatrices (BRDF, BSDF) for materials and coatings within a spectral range of (0.3-2.5 micron)

A goniospectrophotometric installation records in the automatic mode an angular distribution of relative intensities of the scattered radiation by the method of comparing with the reference.

The principle of measuring reflection indicatrices for materials is explained with the help of figure 10. As radiation source –1, an arc zirconium lamp is used, high-aperture monochromator - 3 determines a narrow spectral interval, and after that, the probing radiation is incident with the help of mirror optics on sample investigated –4, which is fixed in the rotating device having a reference limb for setting an incident angle. As a radiation source, superbright light emitted diodes of visible and IR ranges, the spectrum of which is narrowed down by the monochromator, and also lasers may be used.

The receiving part of the goniospectrophotometer is situated on disk –5 rotating within the range of (0 - 360°), having a diameter 600 mm, the radiation is collected by the mirror lens and focalized on photoreceiver - 6 (for visible region FEU-76). The angular aperture of the photoreceiver device may be changed with the help of diaphragm. Reading the angle of rotation is performed for the disk rotating together with the photoreceiver to an accuracy of not more than 30 angular minutes.

Recording the intensity of radiation scattered is performed by the method of synchronous detection at the frequency of approximately 400 Hz, as formed by reference channel –2, having radiation modulator -12 and photoreceiver –13. As a detector, phase-sensitive voltmeter -10, so-called “Lock-in”, is used. In order to digitize the signal detected, 20-digit galvanically decoupled analog-to-digital converter having autocalibration is used. Management of the measurement process

is performed with the help of personal computer –8 through interface control block - 9, driving a rotation of the disk having a receiver block and turning monochromator's diffraction gratings are performed in accordance with a programme using stepping motors 7, 11.

Within the measurement device, there is also a controlled system of polarizer-analyzer, which allows to set any condition of polarization for the probing radiation and to record the radiation scattered with a specific polarization. The general view of the measurement installation is provided in figure 11.

In the present work, measuring reflection indicatrices was performed at incident angles of the probing radiation ($\lambda=550$ nm) of 0° and 67° , in case of diffusively reflecting materials, and 10° and 67° , in case of mirror reflecting materials, in order to record a mirror component of the radiation reflected. Measurements were performed within the plane of incidence, having a natural condition of the probing radiation polarization (without using polarizer – analyzer system). As a reference sample for comparison while measuring an angular dependency of the strength of the reflected light within a visible region, barium sulfate was used. An angular resolution is not worse than 1° while measuring.

The ordinate axis is an amount of the relationship (I/I_0) , the intensity of light reflected from surfaces of the fabric samples investigated in the given direction $I(\theta_r)$ to the intensity of light reflected by the reference sample of barium sulfate (Lambert reference for $\lambda=550$ nm) in the normal direction to its surface I_0 . Signals proportional to intensities $I(\theta_r)$ and I_0 , were measured with identical fixed parameters of the measurement installation.

In order to coordinate dynamic ranges for mirror and diffusively reflecting samples, high-precision neutral optical radiation attenuators of 1:50, 1:100, 1:200 were used.

As examples, the reflectance indicatrices for two incident angles $\theta_i = 0^\circ, 67^\circ$ are presented in figures 12 and 13, in respect of different types of materials, respectively: TRSO-TsM is a coating having a high value of diffuse reflection coefficient, close to the Lambert sample for $\lambda=550$ nm; EKOM-1P is a coating having both mirror, and diffuse components for the reflected radiation; AK-512 (black) is a coating having a low reflection coefficient.

In case of the normal radiation incidence, the shape of indicatrix for TRSO-TsM is close to the circumference having a diameter of approximately 1 in polar coordinates. Similar shape is observed for the ideal Lambert sample. It is seen in figure 13, that there is virtually no maximum in the direction of the mirror reflection in the curve corresponding to the indicatrix for TRSO-TsM at $\theta_i = 67^\circ$. Those maxima reach a considerable value in case of inclined incidence of radiation for the two other samples.

There is presented in figure 14 reflection indicatrices for enamel: AK-512 (white) at $\theta_i = 67^\circ$ before and after an electron action. One observes a decrease in the mirror peak and an increase in the diffuse component of reflectance characteristic of increasing roughness (destruction) of the near-surface layer.

3.5. Measurement of the coefficient of solar radiation absorption A_s

Measurements of the coefficient of solar radiation absorption A_s were performed in the course of testing using a laid-on integral photometer FM-59M. The photometer was designed for the measurement of the integral reflection coefficient R_s by the relative method, and the determination of A_s for the extra-atmospheric solar radiation using the formula of:

$$\alpha_s = 1 - R_s$$

The source of radiation was a quartz halogen lamp, radiation receiver was a controlled block of silicon and germanium light emitted diodes. The limit of root-mean-square deviation for a random component of the main absolute error was 0.5 %. The incident angle of the radiation amounts up to 16° in respect of the normal to the sample surface. The measurement head was portable and made it possible to rapidly measure cumbersome and small samples.

We did not possess a system for the measurement of the spectral reflection coefficient and A_s immediately in the vacuum chamber, however, we have a technique for taking into account a restoration of optical characteristics after extracting a sample into the air in order to determine an integral coefficient A_s , consisting in measuring dynamics of its changing, immediately after extracting the sample into the air. The result of measurement for the first point of this dynamic dependence was obtained in 2 minutes after the sample contacts the air. The accuracy for measuring A_s varied from 0.5 % of the value to be measured for the initial point of testing to 3 % in the final point.

The photometer does not make it possible for measurements to be performed in case of A_s for samples of materials, which transmit the radiation within the wavelength range (0.25-2.5 micron). However, for a number of materials, for example, fabrics, the integral transmittance T_s under action of space environment factors most probably remains unchanged (it is believed that the radiation penetrates only holes in the fabric), therefore it does not contribute to changing ΔA_s . In order to determine absolute (not shifted) values A_s , it is necessary to determine the transmittance coefficient T_s , for example, using spectral measurements for the transmittance coefficient by a spectrophotometer, or performing additional measurements for a transmitting sample, having a mirror put under it, by an integral photometer. At the same time, in the second case, it is rather difficult to obtain a relationship for calculating T_s for the system “transmitting scattering layer – mirror”.

In case of thin films, the coefficient T_s will not remain constant under action of space environment factors, it would be necessary to determine variations ΔR_s and ΔT_s , so that to obtain ΔA_s . In any case, it is more preferred to determine T_s by performing measurements carried out using a spectrophotometer.

3.6. Measurements of integral emission ability for materials - ϵ and coatings

TRM-I integral radiometer is designed to measure an emission ability for planar opaque samples by the method of comparing. The region of spectral sensitivity for the instrument is (4÷40 micron). The source of radiation is a heater made as black body model, the receiver is bolometer situated in the cavity of the heater. The modulated radiation flux reflected by the sample is focused with the help of a mirror ellipsoid at the receiver plate of bolometer. The carrier signal is proportional to the difference between fluxes as reflected from the mirror surface of the modulator and from the sample investigated. In order to calibrate the instrument, the model of the absolute black body ($\epsilon=0.99$) and golden mirror ($\epsilon=0.035$) are used. The random component of measurement error is equal to 2 %. The general view of the thermoradiometer is represented in figure 16. The measurements are performed in premises having a stable temperature, the samples investigated and the black body are maintained at the thermostatic plate before measurement.

3.7. Measurements of the spectral coefficient for the total diffuse and mirror reflection in the region of wave lengths of 220 - 2600 nm.

Measurements of the spectral coefficient for the total diffuse and mirror reflection in the region of wave lengths of 220 - 2600 nm were performed using Lambda-9 (Perkin-Elmer) spectrophotometer equipped with a standard integrating sphere having a diameter of 60 mm. The probing light beam was incident on the sample at the angle of 8° to the normal drawn to the sample surface, and illuminated the plate having dimensions of approximately 5×5 mm. The reflected and diffuse scattered light is collected in the sphere, and its intensity is registered by a photomultiplier and PbS receivers. As a standard sample, the white reference - BaSO_4 powder – was used, as deposited onto the planar aluminium plate, having a reflection of 97 % in the whole indicated spectral region of measurements. Measuring spectra for standard samples was performed in the automated mode using a standard software. Recording experimental values was carried out with an increment of not more than 5 nm. The spectrum obtained was represented on the monitor screen,

and afterwards exported into the graphical editor Microcal Origin for further processing. Values of the spectral coefficients of the total reflection R_λ were determined using the relationship of:

$$R_\lambda = \frac{I_{\lambda,R}}{I_{\lambda,0}}$$

where $I_{\lambda,0}$ is an intensity of the incident light, $I_{\lambda,R}$ is the total intensity for the reflected and scattered light.

The base line is drawn in accordance with the reference sample BaSO_4 at the level of 97 % within the measured region of wave lengths. Under the same conditions, reflection coefficients are measured for the planar aluminum mirror and samples investigated.

The mathematical processing for spectral curves with the purpose of determining the integral coefficient of solar radiation absorption within the region of wave lengths of 220 - 2600 nm is carried out in the following way. The curves are normalized using a spectral distribution of solar extra-atmospheric radiation (model AM0).

After that, an integral is calculated using normalized curves. The coefficient α_s is calculated with the help of the formula:

$$\alpha_s = \frac{\int R_{0\lambda,T} d\lambda - \int R_\lambda R_{0\lambda,T} d\lambda}{\int R_{0\lambda,T} d\lambda}$$

where $\int R_\lambda R_{0\lambda,T} d\lambda$ is an integral for the normalized reflection curve of a sample; $\int R_{0\lambda,T} d\lambda$ – is an integral under the curve of 100% reflection.

There is in figures 17, 18 a typical view of spectral reflection curves for enamels AK-512 and 40-1-28 before and after irradiation using protons having an energy of 500 keV. There is presented in table 3 values for coefficients of the solar radiation absorption in case of enamels before and after an electron or proton action, as calculated using spectral data.

Table 3.

Values of the solar absorptance of enamels before and after exposure to electrons and protons

	Pristine	Electrons, 40 keV, 10^{17} cm^{-2}	Electrons, 100 keV, $2 \times 10^{16} \text{ cm}^{-2}$	Electrons, 200 keV, $2 \times 10^{16} \text{ cm}^{-2}$	Protons, 40 keV, 10^{16} cm^{-2}	Protons, 150 keV, $2 \times 10^{16} \text{ cm}^{-2}$	Protons, 300 keV, $2 \times 10^{16} \text{ cm}^{-2}$	Protons, 500 keV, $2 \times 10^{16} \text{ cm}^{-2}$
EKOM-1	0.257	0.399	0.256	0.251	0.456	0.559	0.691	0.577
TRSO-TsM	0.052	0.199	0.074	0.139	0.565	0.561	0.525	0.652
AK-512								
(white)	0.173	0.306	0.226	0.244	0.584	0.583		0.544
40-1-28	0.071	0.516	0.164	0.322	0.562	0.537	0.533	0.237

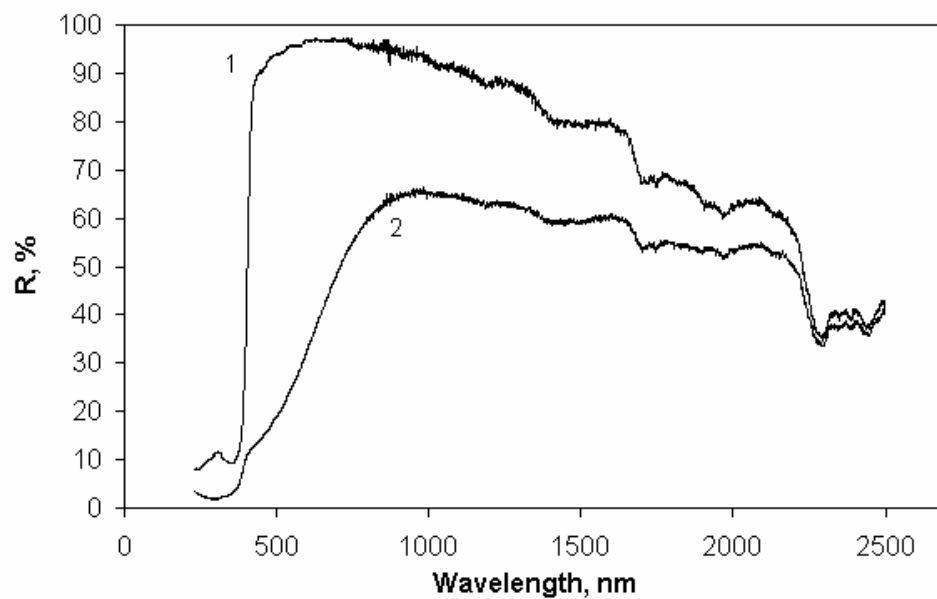


Fig. 17. Reflectance spectrum of the AK-512 enamel (white), pristine (1) and irradiated with protons (2). $E_p=150$ keV, proton flux intensity 5×10^{12} p/cm²s, absorbed fluence 2×10^{16} p/cm²

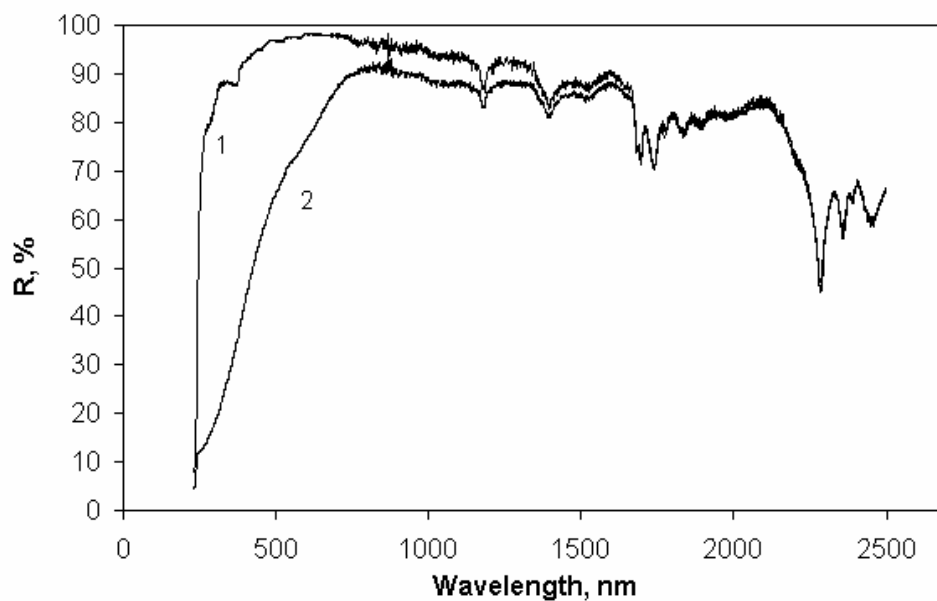


Fig. 18. Reflectance spectrum of the 40-1-28 enamel, pristine (1) and irradiated with protons (2). $E_p=500$ keV, proton flux intensity 5×10^{12} p/cm²s, absorbed fluence 10^{15} p/cm²

4. Current status of the progress of the technical work

The work under the project has been fulfilled.

5. Cooperation with foreign collaborators

- exchange of scientific materials (information, computer software and data, samples)
- signing protocols (along with a short description)
- joint scientific research
- professional trips to the foreign collaborator organizations/visits of the foreign collaborator representatives
- seminars, thematic meetings organized by the project participants
- joint participation in the work of international conferences

The progress of was discussed with representatives of the partner organization: the European Office of Aerospace Research and Development (EOARD, London). The discussions took place during visits of EOARD representatives to the leading institution (MIFI, Moscow) in August 2002, June 2003 and May 2004.

Travel to foreign organizations or participation in seminars and conferences during the duration of the project was not planned for.

6. Information concerning usage of the project results

Transfer of the present scientific-technical report from the exporter (MIFI) to the partner (EOARD) is performed on the basis of the license as issued by the Federal service of export control of the Ministry of Defense, and restricted by limitations as contemplated by its conditions.

Deputy Rector of MIFI for Studies, Professor

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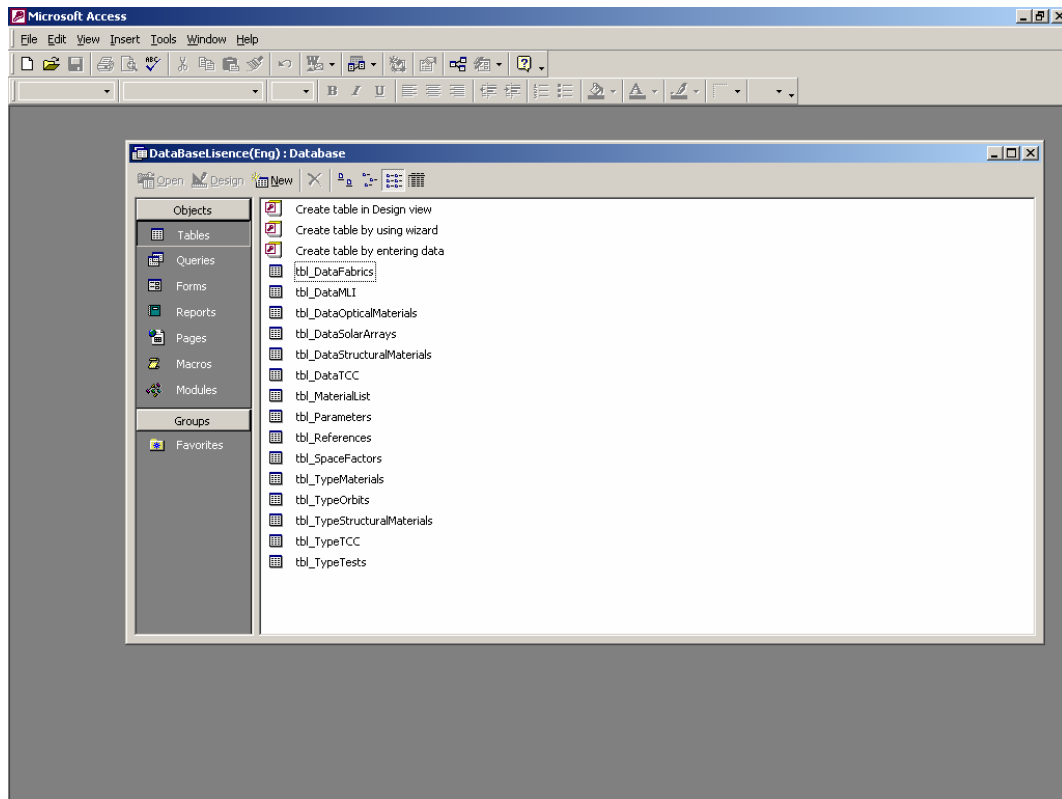


Figure 1.

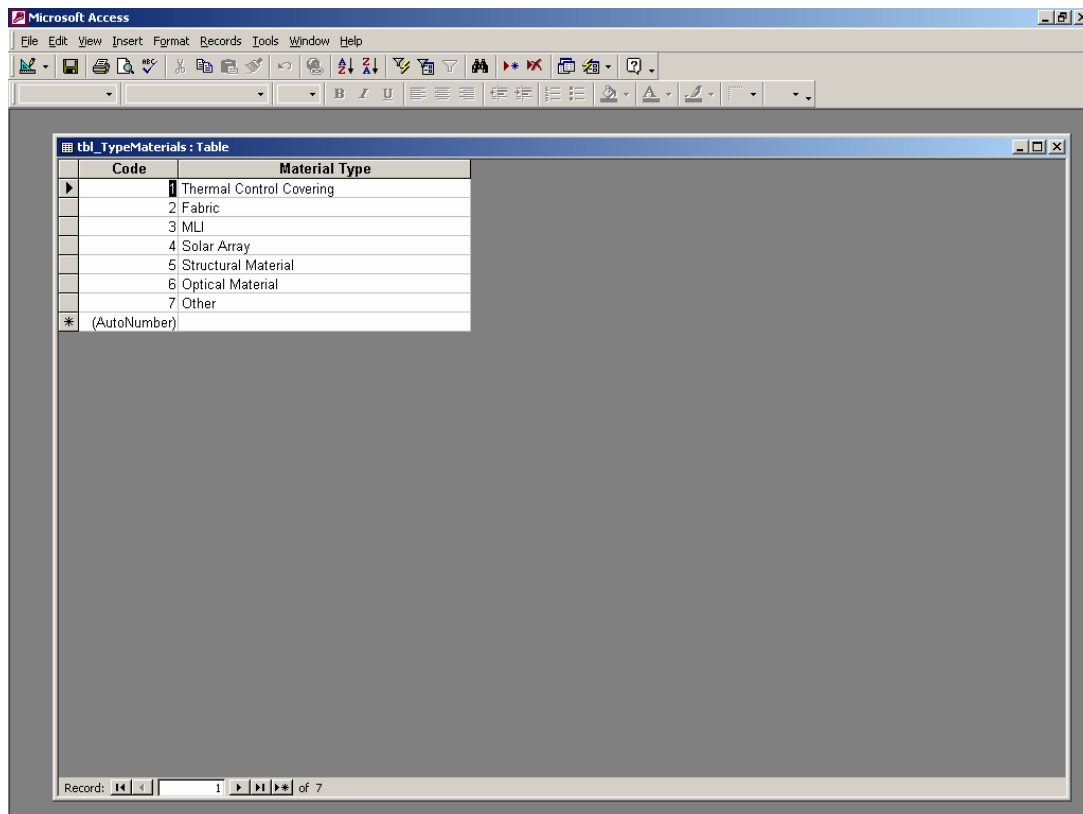


Figure 2.

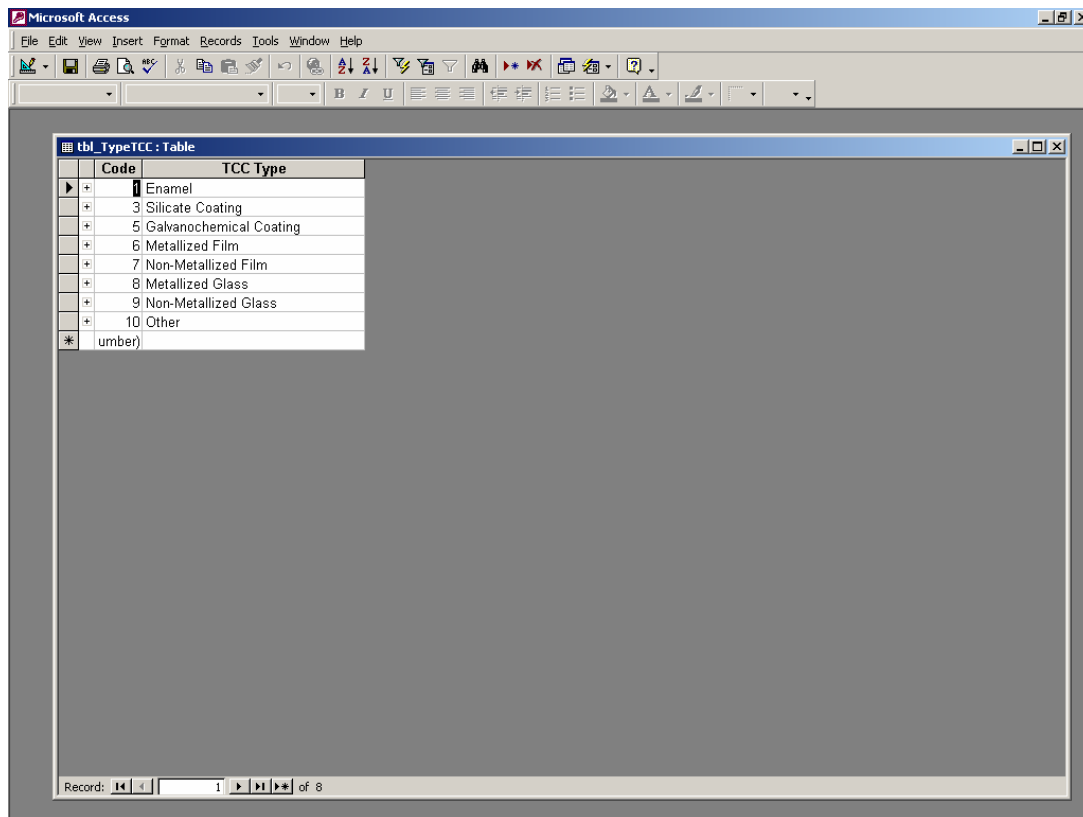


Figure 3.

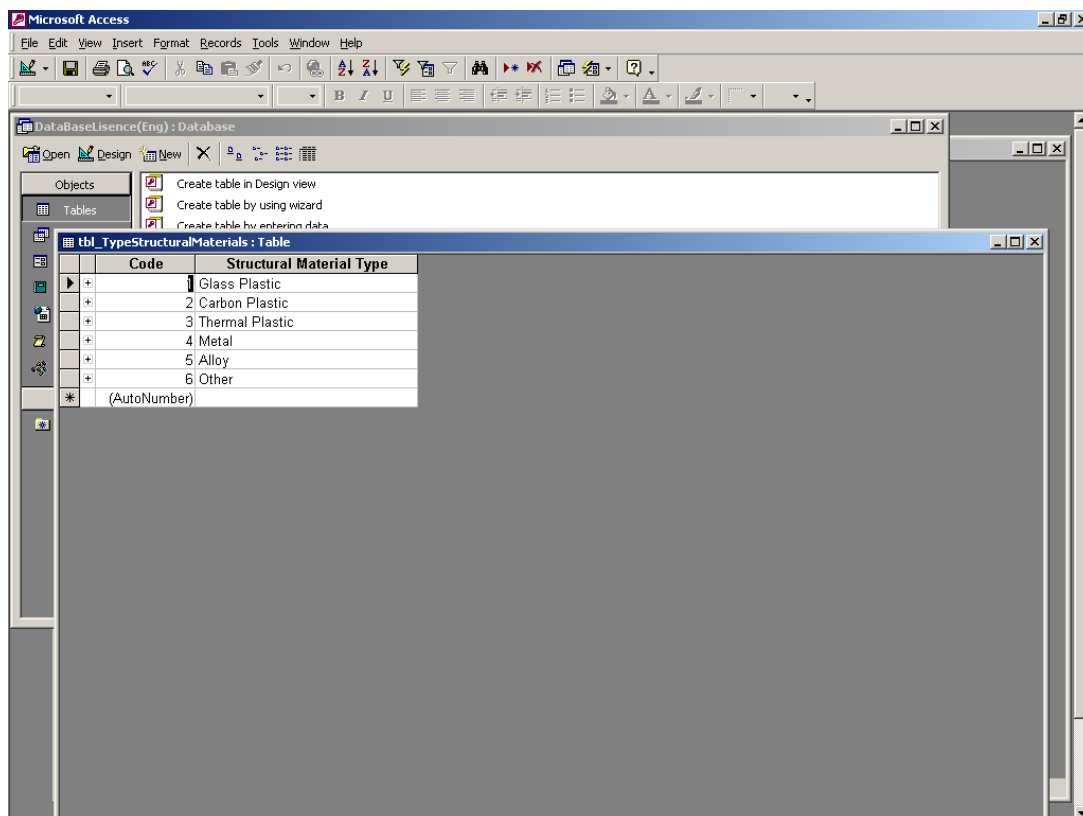
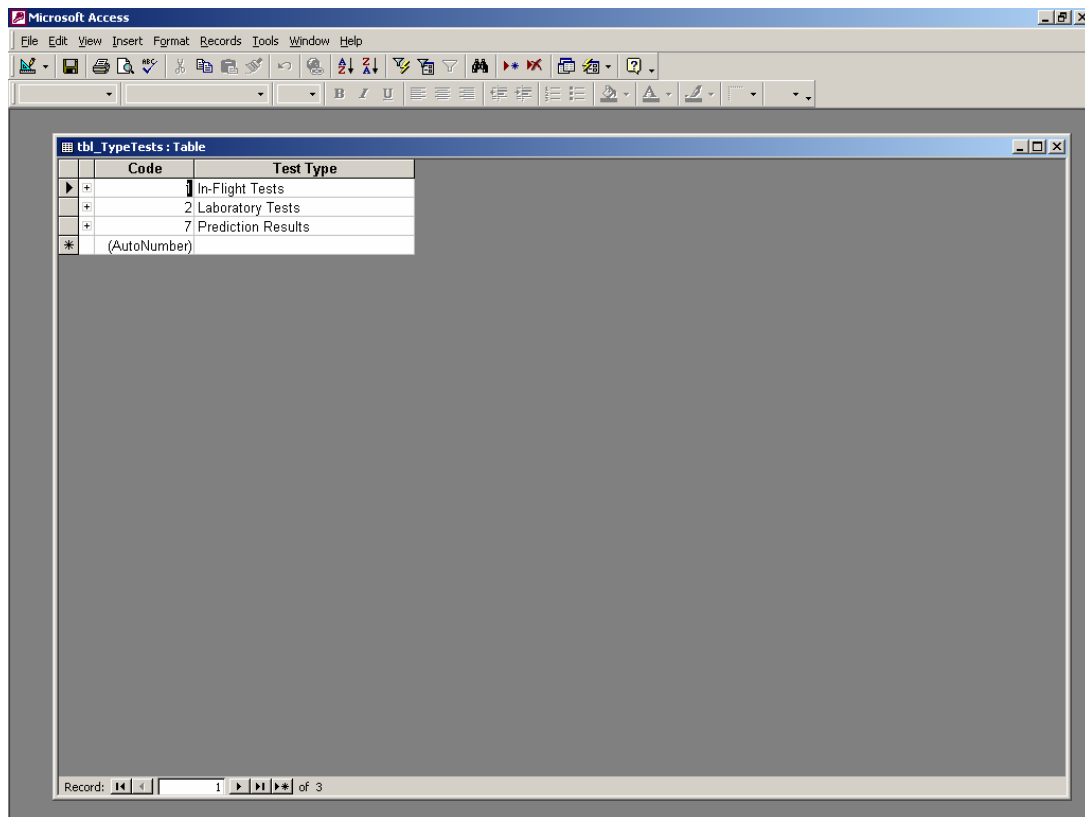


Figure 4.



Microsoft Access

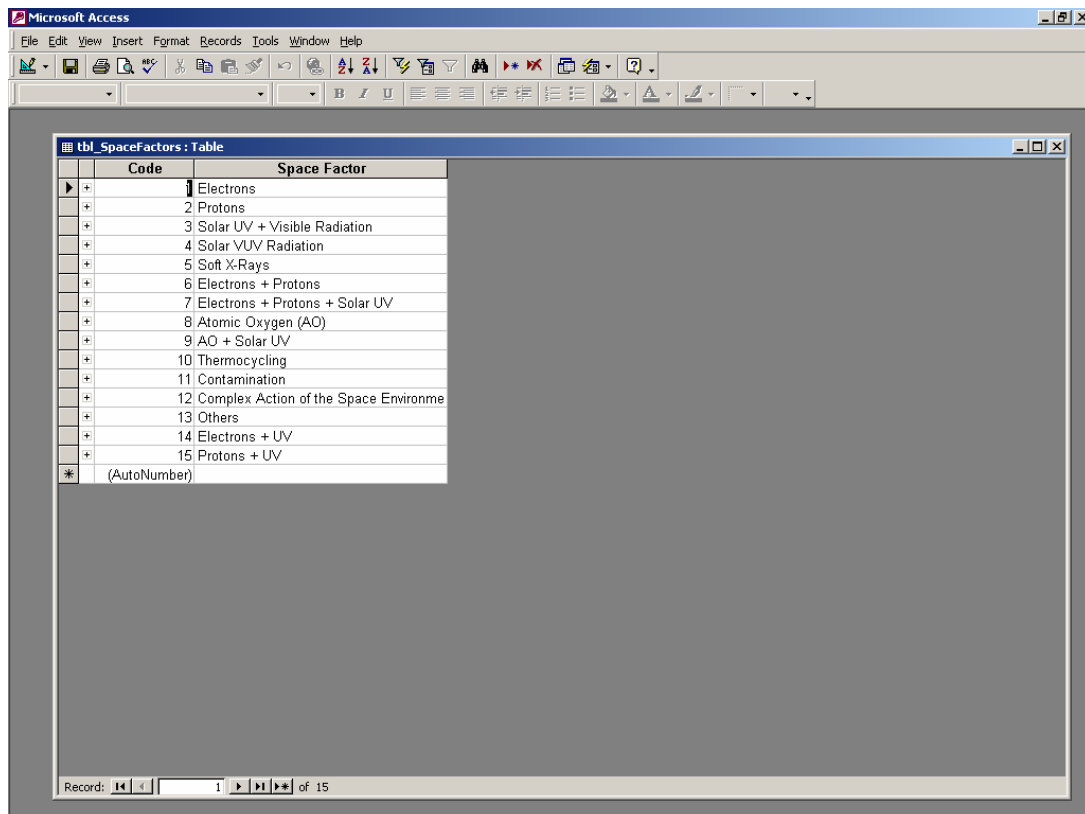
File Edit View Insert Format Records Tools Window Help

tbl_TypeTests : Table

Code	Test Type
1	In-Flight Tests
2	Laboratory Tests
7	Prediction Results

Record: 1 of 3

Figure 5.



Microsoft Access

File Edit View Insert Format Records Tools Window Help

tbl_SpaceFactors : Table

Code	Space Factor
1	Electrons
2	Protons
3	Solar UV + Visible Radiation
4	Solar VUV Radiation
5	Soft X-Rays
6	Electrons + Protons
7	Electrons + Protons + Solar UV
8	Atomic Oxygen (AO)
9	AO + Solar UV
10	Thermocycling
11	Contamination
12	Complex Action of the Space Environme
13	Others
14	Electrons + UV
15	Protons + UV

Record: 1 of 15

Figure 6.